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Electromechanical Actuators Affected by Multiple Failures: Prognostic Method based on Spectral Analysis Techniques

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Abstract. The proposal of prognostic algorithms able to identify precursors of incipient failures of primary flight command electromechanical actuators (EMA) is beneficial for the anticipation of the incoming failure: an early and correct interpretation of the failure degradation pattern, in fact, can trig an early alert of the maintenance crew, who can properly schedule the servomechanism replacement. An innovative prognostic model-based approach, able to recognize the EMA progressive degradations before his anomalous behaviors become critical, is proposed: the Fault Detection and Identification (FDI) of the considered incipient failures is performed analyzing proper system operational parameters, able to put in evidence the corresponding degradation path, by means of a numerical algorithm based on spectral analysis techniques. Subsequently, these operational parameters will be correlated with the actual EMA health condition by means of failure maps created by a reference monitoring model-based algorithm. In this work, the proposed method has been tested in case of EMA affected by combined progressive failures: in particular, partial stator single phase turn to turn short-circuit and rotor static eccentricity are considered. In order to evaluate the prognostic method, a numerical test-bench has been conceived. Results show that the method exhibit adequate robustness and a high degree of confidence in the ability to early identify an eventual malfunctioning, minimizing the risk of fake alarms or unannounced failures.

INTRODUCTION

Actuators are component responsible for moving or controlling a mechanism or system. They transfer power of various sources (mechanical, electrical, hydraulic, or pneumatic) into motion by means of gearings. With regard to flight commands, in the last years, actuators based on the hydraulic power have been replaced by Electromechanical Actuators (EMAs) because they offer more advantages: easier maintenance reduced global weight, absence of hydraulic fluid that is often pollutant and inflammable. As some actuators are safety critical, in order to guarantee the system to always operate in safety conditions, it is necessary to schedule programs of maintenance and redundancy; nevertheless, even if, at present, they are the most common means to diminish the risks, in case of unpredicted and severe operative scenarios, they can be insufficient and it becomes necessary to forecast unscheduled maintenance. In this context, there is a discipline called Prognosis and Health Management (PHM) that, through the monitoring of functional parameters of the sys-tem involved, tries to predict failures at early stage and to determine the source of irregular behaviors. In case of EMAs, the PHM can be applied in a more efficient way than in case of hydromechanical or electro-hydraulic actuators, because, on electrical systems, additional sensors are not required. In fact, the application of the PHM strategies normally entails the monitoring of a set of parameters in the form of electric signals and they often use the same sensors of the control scheme and system monitors. In this paper, we take into account electromechanical actuation systems. Concepts and results are based on the design of reliable and fast prognostic Fault Detection and Identification (FDI) routines that are part of a broader research activity focused on the diagnosis model-based. This paper presents a study focused on the development a prognostic technique able to identify proper failure precursors alerting that degrading performances of an aeronautical electromechanical actuator exhibiting anomalous behaviors. In particular, two kinds of non-linear physical behaviors are considered: partial stator single phase turn to turn short-circuit (SC) and static rotor eccentricity (SRE).

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To assess the robustness of the proposed techniques, based on a typical Spectral Analysis approach, an appropriate simulation test environment has been developed. Simulations have then been run with progressive SC and SRE while the EMA model is subjected to different parameters configuration; the algorithms correctly sort out the failure precursors and make a correlation between SC and SRE percentages and the calculated operating maps to identify and evaluate incoming failure. Results show that an adequate robustness and confidence has been gained in the ability to early identify the EMA malfunctioning minimizing the risk of false alarms or unannounced failures.

EMA REFERENCE MODEL

As reported in [1], a standard EMA employed in primary flight control systems consists of:

1. An actuator control electronics (ACE) that, comparing the commanded position (FBW) with the reference one, closes the feedback loop, elaborates the corrective actions and generates the reference current I_{ref}.
2. A Power Drive Electronics (PDE) that sets the three-phase electrical power.
3. An electrical motor, often BrushLess Direct Current (BLDC) type.
4. A gear reducer that decreases the motor angular speed (RPM) and increases its torque to the needed values.
5. A system that transforms rotary motion into linear motion; ball or roller screws are usually preferred to acme screws because, having a higher efficiency, they can perform the conversion with lower friction.
6. A network of sensors used to close the feedback rings that control the whole actuation system.

The main goal of this research is to propose a technique able to identify early signs of EMA damaging; at this purpose, the authors considered a dedicated numerical model previously developed [2] and implemented it in MATLAB/Simulink® environment. The model, reported in Fig. 1, is made up of the following six subsystems:

1. An input block that generates different position commands (Com).
2. A subsystem that simulates the actuator control electronics, closes the feedback loops and generates the reference current I_{ref} (Controller) [3].
3. A subsystem that evaluates the torque developed by the electrical motor as a function of the voltages generated by the three-phase electrical power regulator (BLDC ElectroMec model) and that simulates the power drive electronics and the trapezoidal BLDC electromagnetic model [2].
4. A subsystem simulating the EMA mechanical behavior through a 2 dof dynamical system (EMA Dynamic).
5. An input block simulating the aerodynamic torques acting on the moving surface controlled by EMA (TR).
6. A block simulating the EMA monitoring system (Analyses & Graphs).

This model can simulate the dynamic response of the real actuation system: it considers the consequences of progressive faults, the effects due to dry friction and backlashes acting on mechanical parts, the conversion from analogic to digital of the feedback signals (ADC), the electrical noise acting on the signal lines and the position transducers affected by electrical offset.

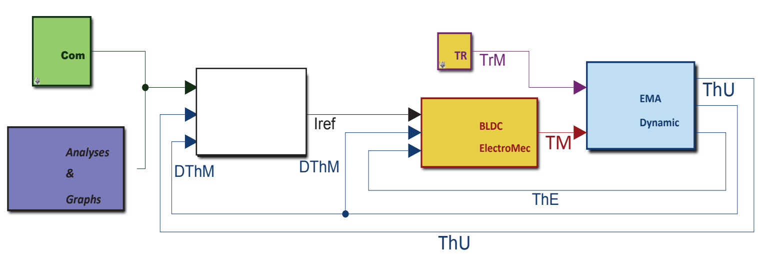

FIGURE 1. Proposed EMA block diagram.

EMA FAILURES AND PERFORMANCE DEGRADATIONS

The employment of EMAs in aeronautics is quite recent, so statistics about their failures are not yet consistent. Anyhow, it is possible to refer to four main groups of failures: electronics (i.e. Controller) and sensors failures, electric motor, mechanical or structural failures. As shown in [4], main failures in BLCD motors are due to progressive stator coil short-circuits (due to thermal effects that could compromise the insulation of the coil windings) and rotor static eccentricity (caused by bearing wears). Short-circuits usually start between a few coils belonging to the same phase (coil-coil failure) and then spreading to adjacent coils.

In fact, in short-circuited coils the voltage remains the same and the resistance decreases; as a consequence, a high circulating current arises and generates a localized heating in conductor that helps the propagation.

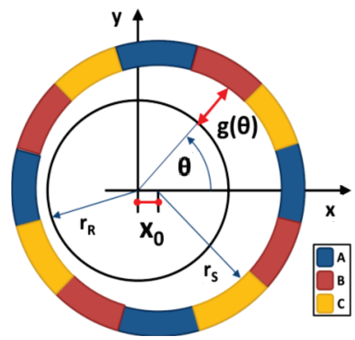

FIGURE 2. Reference system for the definition of rotor static eccentricity ζ.

Rotor static eccentricity consists in a misalignment between its rotation axis and the stator axis of symmetry. It is due to tolerances and imperfections introduced during motor construction or to gradual increase of wear of the rotor shaft bearings. Whenever it occurs, the motor, supposed to have more than one polar couple, generates a periodically variable magnetic flux, as the air gap varies during rotation (Fig. 2) as a function of the rotor position ϑ_r:

$$g(\theta) = g_0(1 + \zeta \cos(\theta)) \quad where \quad \zeta = \frac{x_0}{g_0} \tag{1}$$

In this context, taking into account coil short-circuit and rotor static eccentricity, authors have studied the consequences of faults on the performances of the servomechanism. [2, 5] Failures and their effects on the electrical features of the BLDC motor (e.g. winding resistance, inductance and back-EMF) have been simulated through a simplified numerical model, according to [6]. In particular, the authors simulated the effects of faults affecting the magnetic coupling between stator and rotor varying values and angular modulations of the back-EMF coefficients. Executed in the BLDC ElectroMec model block (Fig. 1), this method acts on the three back-EMF constants Ce_i (one for each branch) modulating their trapezoidal reference values Ke_i as a function of coil short circuit percentage, static rotor eccentricity ζ and angular position ϑ_r:

$$ke_i = Ke_i \cdot Ce_i \cdot (1 + \zeta \cdot cos(\vartheta_r)) \quad - \quad i = a, b, c \tag{2}$$

The so obtained constants (ke_a, ke_b, ke_c) are then used to calculate the counter-electromotive forces induced on the corresponding stator windings and, therefore, to evaluate the mechanical torque contributions generated by the three motor phases. As reported by [7, 8], the evaluation of precursors permits to adopt countermeasures despite quite fast propagation of sensors' and electrical components' failures. It must be noted that, with respect to other EM models available in literature, the numerical model shown in the previous sections is able to calculate the instantaneous value of each current phase (I_a, I_b, I_c) also in case of unbalanced electromagnetic system (e.g. partial short circuit on a stator branch or rotor static eccentricity); then, it is possible to correlate the progressive faults with the dynamic response of these signals (used as failure precursors) by means of an algorithm, based on the Fourier spectral analysis, that evaluates the filtered phase currents; for this purpose, each phase current is filtered by three low pass signal filter, in order to attenuate noise and disturbances [9]. It must be noted that, according to [ESREL 2015], the aforesaid spectral analysis is based on the Fourier Transform (FT), a mathematical instrument that changes the time domain representation into a frequency domain representation, and which has many applications in physics and engineering. In particular, as shown by the authors in [1], the proposed method elaborates the current signals by means of the Discrete Fourier Transform (i.e. the equivalent of Continuous Fourier Transform for a signal known only at N samples time during a finite Time acquisition [10]). Given that the Discrete Fourier Transform (DFT) approximates the Fourier Transform since it provides only for a finite set of frequencies during a limited acquisition time, it may be subject to numerical problems of aliasing and leakage (i.e. corrupted frequency transforms which can be obtained when trying to calculate the DFT of a non-periodic signal). Generally, for most waveform of real data it is not possible to reduce leakage effects without a specific data modification called "Windowing" [11]: a suitable cosine function modifies the whole signal to taper the samples towards zero at both endpoints without discontinuity with a hypothetical next period. It should be noted that, rather than performing DFTs, Fast Fourier Transform (FFT) calculations are often preferred in order to reduce the number of involved multiplications [12, 13, 14]: in particular, the authors' numerical module uses FFTs with "Hanning" windows [15] (i.e. a type of windowing often used for general purpose applications in spectral analysis). These spectral techniques are merged together and implemented into the proposed numerical module that processes all filtered phase currents deriving from each considered combination of faults and correlates these failures with the corresponding failure precursors, generating a simulated "operating map". Once defined, these maps allow developing dedicated on-board or portable devices, equipped with embedded versions of the proposed spectral analysis algorithms, able to perform FDI during preflight tests or calendrical maintenance.

EMA SPECTRAL ALGORITHM AND OPERATING MAPS

As previously reported, authors propose an innovative prognostic model-based technique able to perform an early identification of symptoms of an EMA degradations. The entire simulation time test amounts to one second and, for each simulated actuation test, all filtered phase currents (I_{fa}, I_{fb}, I_{fc}) are acquired and used as prognostic precursors to evaluate the percentage of Short coil for a single alimentation phase. The Root Mean Square (RMS, also known as quadratic mean) of a given signal time history represents a measure of overall energy and it is often used to extract signal features for diagnostic analysis, prognosis and trending data. In order to avoid the aforesaid numerical problems of aliasing, the time history of the considered signal must be digitized at a particular sample rate (for a total of N samples), then RMS value can be estimated by:

$$RMS = \sqrt{\frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{x(i)}^2} \tag{3}$$

For each filtered phase current (I_{fa}, I_{fb}, I_{fc}) a *RMS* value is calculated as a function of the percentage of turns of the stator coils still not short-circuited (*Ni*, where $i = a, b, c$ refers to the different stator phases of the three-phase BLDC motor); operatively speaking, the results reported in this paragraph are calculated as a function of a progressive SC acting on the coil of the phase "*a*", with *Na* varying from 75% to 100% with a 1% increasing step. The results are three signals, called $I_{a\ RMS}$, $I_{b\ RMS}$ and $I_{c\ RMS}$, which evolve as a function of *Na* as shown in Fig. 3: it must be noted that, in this case, the rotor static eccentricity is fixed to zero. It must be noted that, with progressive SC coil degradation of the single phase "*a*", all the alimentation phase evolves increasing current *RMS* as function of *Na*. However, as shown in Fig.3, the phase affected by progressive short-circuit puts in evidence an increasing trend of phase current higher than the other ones. The increasing trend for shorted phase "*a*" identifies two critical points, called Crossing Points, in which the filtered phase current $I_{a\ RMS}$ crosses the initially higher value of the corresponding currents $I_{b\ RMS}$ and $I_{c\ RMS}$ (the SC acting on phase "*a*" unbalances the stator circuit influencing also the other phases, although these are still operating in nominal conditions, modifying the corresponding RMS currents).

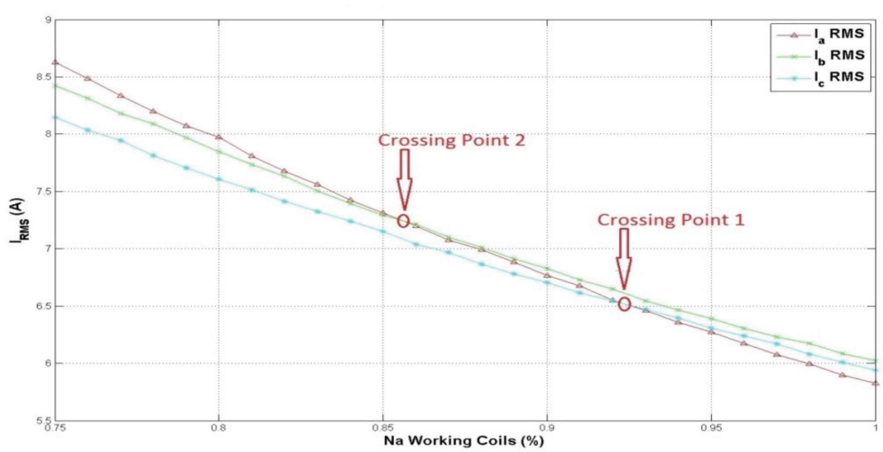

FIGURE 3. Evolution of the three RMS phase currents as a function of *Na* - Rotor Static Eccentricity = 0%.

The Crossing Points give important information to evaluate corresponding short coil degradation percentage on evaluating RMS of filtered phase currents calculated by model based simulation environment. Therefore, the proposed methodology allows to evaluate with suitable accuracy the working coils percentage (e.g. *Na*) for a single damaged phase using the abovementioned failure map (Fig. 3) by considering the so obtained Crossing Points as results of a real measurement on operational field under the same boundary condition for the numerical simulation test. The model-based test bench considers a specific EMA model considering a set of technical parameter as input of simulation runs but it's possible to calculate specific failure maps to evaluate short coils degradation by changing the input technical parameters. The abovementioned evaluation method is described considering a fixed rotor static eccentricity equal to zero, but this simplified approach doesn't allow to give an inclusiveness description of short coils degradation phenomena because rotor static eccentricity have a strong influence to the method results. Indeed, both rotor static eccentricity and short coil degradation cause different effects on prognostic precursors used in the described method based on evaluation of RMS filtered phase currents. The rotor static eccentricity due to wear of EMA mechanical components reduces clearance between rotor and stator surfaces, in the proposed simulation the phase "*a*" is interested by the minimum of air gap. Therefore, it's possible associate to minimum clearance a minimum magnetic resistor, so the RMS filtered phase current values decrease related to nearly the same alimentation power. The increasing rotor static eccentricity causes effects opposed to the effects induced by short coils phenomena where the RMS filtered current increases, for the damaged phase, strongly with increasing coils degradation. As reported in Fig. 4, these opposite effects, associated to different type of degradations, cause a sliding of the two Crossing Points positions on failure maps, in which the rotor static eccentricity is equal to 50%.

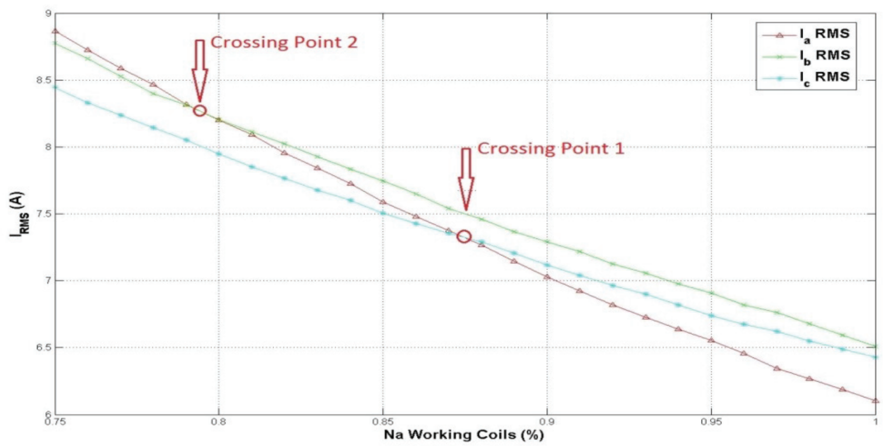

FIGURE 4. Evolution of the three RMS phase currents as a function of Na - Rotor Static Eccentricity = 50%.

The increasing rotor static eccentricity modifies the position of Crossing Points on failure maps allowing evaluating corresponding variable *Na* working coils percentage more critical than the same Crossing Points allow in condition of rotor static eccentricity equal to zero. Therefore, in case of rotor static eccentricity percentage greater than 30%, it is possible to associate Crossing Points position related to a high warning operational condition, that need maintenance tasks. It must be noted that, from a prognostic point of view, the RSE magnitude typically considered is smaller the 50%; indeed, the RSE upper limit for FDI algorithms is often around 25 - 30% (bigger RSE percentages, producing macroscopic effects on EMA behaviors, involve diagnostics and monitoring strategies). In general, rotor static eccentricity percentage lower than 30% presents failure maps able to evaluate minimal percentage of short coil degradation, representing a useful feedback to increase safety margin. The rotor static eccentricity is often due to wear phenomena that, typically, evolve more slowly with respect to electric progressive faults affecting BLDC motor; in particular, the time scales of short coils degradations are usually similar (at least as orders of magnitude) to other electrical aging degradations. These differences between their evolution time scales allows to estimate the rotor static eccentricity by using the methodologies, also based on spectral analysis, previously developed by the authors [1, 2, 4]. Given that these FDI methods for evaluate rotor static eccentricity could be influenced by short coils degradation, it will be case study for further investigation occurrences in other to improve identification and evaluation technique presented in this work.

CONCLUSIONS

The proposed model-based approach allows calculating specific operating maps for many different EMA models: modifying defined sets of technical parameters, it is possible to adapt the performances of the numerical system to a given type of EMA and, so, define the corresponding operational map in order to evaluate short coils degradation taking into account rotor static eccentricity effects. Actual EMA failure precursors, directly acquired by on-board monitoring systems, are compared with the corresponding calculated operating map in order to evaluate, during a preflight test, the percentage of working short coil degradation affecting a single alimentation phase avoiding degraded flight command performances improving safety margin. Once defined the operational maps simulating EMA numerical model, integrated with the authors filtered RMS phase current module, it is possible to have an adequate accuracy to individuate the health state of the actual actuator by performing pre-test flight as indicated in previous paragraphs. Results encourage the extension of the proposed technique in order to investigate more challenging occurrences such as the detailed interactions between electrical (e.g. progressive coils SCs) and mechanical failures due to wear (e.g. rotor static eccentricity, dry friction forces and backlashes acting on mechanical transmission) that, being usually characterized to very different time scales and giving often opposite effects on prognostic precursor analysis, are frequently difficult to evaluate with suitable accuracy. For this purpose the actuator model should be further detailed and new element should be modelled, extending spectral analysis and investigating to these combined failures interactions.

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